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Current status and future prospects of hydropower in Saxony (Germany) compared to trends in Germany, the European Union and the World

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ABSTRACT

Hydropower plays an important role as the main renewable source of energy generation with an installed capacity of 990 GW in 2012 worldwide contributing to climate protection. However, the main sources of electricity generation are large dams contributing to more than 90% of electricity generated from hydropower. In Saxony (ca. 300 hydropower plants with an installed capacity of 88 MW), comparable to most of the other German federal states (Bundesländer, with ca. 7.600 hydropower plants and an installed capacity of ca. 4 GW in total) and industrial nations worldwide the developmental potential for increasing electricity generation by hydropower is almost exploited. Future prospects for development of large hydropower and pump-storage hydropower plants are generally more positive in some countries as the need for storage of surplus electricity generation will increase. Small hydropower might be of increasing interest in developing countries if locations for hydropower that are economical to develop and that can be exploited with respect to environmental protection will be available. Developmental potential for increasing hydropower in Saxony will be mainly the improvement of technical efficiency (refurbishment) of existing hydropower plants and to a much lesser extent the use of existing non-hydropower low head dams that must be not necessarily removed to achieve the environmental objectives for the particular streams according to the Water Framework Directive (WFD). Nevertheless, statutory requirements for environmental protection especially for migratory fish and for improvement of stream ecosystem functions will restrict the future development of hydropower in Germany as well as in most countries of the European Union.

Contents

1. Introduction

Climate change induced by emissions of greenhouse gases (GHG) from anthropogenic activities is the greatest challenge for mankind during the next decades. Main effect of increased anthropogenic greenhouse gas concentrations in the atmosphere is the increase in global mean temperature that could be observed during the last decades [1]. Human use of fossil fuels (especially oil, coal and gas) for total primary energy supply accounts for the majority of global anthropogenic GHG emissions leading to emission of ca. 29 billion tons carbon dioxide (CO_2) in 2009 [2]. Shares to CO_2-emmissions of coal/peat (43%) were the highest followed

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by oil (36.7%), and natural gas (19.9%). Significant lowering of GHG emissions will be urgently necessary to achieve the objective of limiting the increase in global temperature to 2 °C above pre-industrial levels, to which all major emitting countries agreed in the Copenhagen Accord. Several possible options exist to reduce GHG emissions including energy conservation and efficiency, fossil fuel switching, renewable energy, nuclear and carbon capture and storage.

Even assuming a new policy scenario in which fossil-fuel subsidies are completely phased out in all net-importing regions by 2020 (at the latest) and in net-exporting regions where specific policies have already been announced, the world electricity demand continues to grow from 16,819 TWh in 2008 to about 30,300 TWh in 2035 [3]. Renewable energy sources can replace fossil fuels for electricity generation to a certain extent, contributing to the reduction of worldwide CO_2-emmissions. Hydropower is today the most important renewable source for generation of electricity worldwide. Hydropower contributed 16.5% to world electricity generation in 2012, while other renewables including geothermal, solar, wind, biofuels and waste, and heat contributed only 5.2% [4]. Furthermore, many countries actually use the potential to increase the use of renewables for electricity generation, especially non-OECD countries, first of all in Asia [3,5], but also in South America, the Russian Federation and, remarkably for Europe, in Turkey [6]. Nevertheless it is expected that shares of renewable energy sources to worldwide electricity generation will significantly increase from 19% in 2008 to 32% in 2035, but shares of hydropower are expected to remain around 16% while shares of other renewables will significantly increase (e.g. wind power from 1% in 2008 to expected 8% in 2035) [3].

Electricity generation in Germany will be determined during the next years by the phase-out of nuclear power, an energy market reform and climate change policy. Nuclear power phase-out as the consequence of the Fukushima catastrophe will result in a progressively shut down of nuclear power stations as they age – with complete shut-down of all plants estimated to occur by 2022 [7].

Increasing electricity generation by renewables, energy conservation and efficiency in heating, especially thermal insulation of buildings are the main measures to reduce the emissions of 70–80 Mio. t CO_2/a until 2020. Considering the long term period until 2050, the electricity generation by renewables become more important as reducing potentials of other possible measure to reduce GHG emissions decrease by time [8].

Twenty years ago, hydropower was the only renewable energy source contributing significantly to electricity generation in Germany (91% of renewables), while electricity generation by all other renewables together was rather negligible with 1836 GWh in 1992. Nevertheless, the use of hydropower, even small or mini hydropower schemes, cause environmental problems [9] that have to be addressed and considered as the Water Framework Directive [10] demands the protection, enhancement and restoration of streams and rivers with the aim of achieving a good surface water status. Thus, the European Small Hydropower Association recently raised some concern about the implementation of the WFD and the threats to the future development of small hydropower in some EU-member states [11]. The present study reviews available information on the possible development of hydropower electricity generation, comparing worldwide trends to the European Union (EU), Germany and Saxony as a part of Germany, with a long history in hydropower use for different purposes. Focus will be laid on medium, small and mini-hydropower, as no hydropower scheme with an installed capacity >10 MW exist in Saxony (except two pump storage plants), but large hydropower will be mentioned due to its predominant role in electricity generation by renewables. In the following hydropower will be classified into large (installed capacity >10 MW), medium (>1 MW and <10 MW), small (>0.1 MW and <1 MW) and mini (≤ 0.1 MW).

2. Electricity production by hydropower worldwide

Hydropower is rated to be the farthest developed technology of all renewables to generate electricity. Additionally, it is commercially proven and small run-of-river hydropower yield the highest energy payback ratio for all renewables [12]. Water is present and usable all over the year in contrast to wind and solar that are intermittent technologies and only usable when these resources are available.

Hydropower can be used to balance short-term variability in electricity demand, especially for systems with electricity inputs from various energy sources which can result in load imbalances within the grid. Electricity generation capacity and availability by large dams with high water storage capacity is very different from small run-of-river hydropower schemes [13]. Small hydropower depend on natural flow regime of the particular stream and river, with sometimes high seasonal variability, while large dams can be flexibly used to generate electricity, especially during short periods of high demands, due to the storage of a large water volumes. Small hydropower plants are characterized by high load factors (ratio of annual electricity generation to installed capacity), due to the utilization of the whole water potential available to them. The ability of large hydropower (especially pumped storage hydropower) to de-couple the timing of hydropower generation from variable river flows and to store water for later electricity generation enables large hydropower to fulfill the requirements of a peak-load power plant when much electricity is consumed. As a consequence the load factor is often significantly lower compared to run-of-river schemes [13].

Typical energy costs for large hydropower range between 3 and 5 US cents/kWh and are among the lowest costs of all renewables, while typical energy costs for medium and small hydropower ranged between 5 and 12 US cents/kWh, but can increase up to 40 US cents/kWh in rural areas or when the plant is very small (<1 kW installed capacity) or not connected to the grid [14]. Levelised costs considering the main cost components (capital costs, fuel costs and operations and maintenance costs) in relation to the life-span of the hydropower plant can be very competitive against other energy sources, when plants were localized in the best available sites, e.g. mountainous regions accessible for heavy construction equipment with high effective heads for small hydropower [15]. Other renewable sources of electricity generation exhibit levelised costs of 9–40 US cents/kWh for ground-mounted solar PV, 4–16 US cents/kWh for onshore wind power or 5.5–20 US cents/kWh for bioenergy combustion [4]. However, the most favorable sites for hydropower use were almost exploited in most of the industry countries, increasing the levelised costs of new hydropower in less favorable sites, making it uneconomical. Main economic advantage of hydropower are the generally low costs for operation and maintenance, while costs for civil works, especially the costs for construction of the plants and all other necessary constructional works (building of dams, penstocks, etc.) could be very high depending on the design and the location of the plant [16]. Additionally, investment costs (US dollars/kW installed capacity) for small hydropower significantly increase with decreasing effective head and decreasing installed capacity and electricity generation [17]. Nevertheless, the costs of hydropower can be highly variable depending on many site-specific factors, but the lowest investment costs were assumed for projects increasing the capacity of an existing hydropower plant or the installation of new hydropower facilities to an existing dam that was not used for electricity generation before.

Mini-hydropower with an installed capacity of 0.1 MW or less has grown in importance over the last decade and can be an effective means of providing electricity to communities far from industrial centers. In developing as well as in economically aspiring and populous countries like India and Pakistan small hydropower is likely to expand due to the increasing demand of rural electrification [18]. Small infrastructure and hence low construction cost for mini-hydropower schemes in developing countries could be achieved by involving indigenous manufacturer in the civil works [15].

Total electricity generation worldwide was 20,055 TWh in 2009 with a contribution of 3329 TWh by hydroelectricity. Installed capacity of hydropower in 2008 was 952 GW worldwide with the main producers of China (616 TWh and 168 GW installed capacity), Brazil (391 TWh and 71 GW) and Canada (364 TWh and 75 GW) [2]. Large hydropower contributed in 2006 much higher shares (3121 TWh) than small hydropower (ca. 250 TWh) to total electricity generation of hydropower [13]. Worldwide capacity of electricity generation from small hydropower in 2009 was 60 GW and for large hydropower approximately 920 GW [19]. Hydropower is the renewable energy source contributing significantly to worldwide electricity generation when compared to the other renewables. There is still a trend for increasing electricity generation by hydropower, but proportional increase of electricity generation by wind power was higher during the last years (Fig. 1). In 2011 total global capacity for electricity generation by hydropower was accounted for 970 GW with far the highest shares of new contributions in 2011 by China (12.3 GW) followed by Vietnam, Brazil, India, Canada, and Malaysia [20].

Worldwide future outlooks of the US Energy Information Administration [20] projected the highest growth rates for solar (8.7%) and wind power (5.7%) during the period from 2008 to 2035. Although growth rates for hydro were lower (2.0%) it is expected that this energy source will continue to predominate the worldwide installed capacity of renewables in future (Fig. 2). However, most industry nations will increase shares of renewables to electricity generation by other sources than hydro as most locations for hydro that are both economical to develop and also meet environmental regulations already have been already exploited. Other developments were expected for non-OECD countries in which electricity generation mainly from large scale hydropower plants will contribute much higher shares to total installed capacity of renewables [21].

Most member states of the European Union (EU) used hydropower since decades, but shares of hydropower to renewable

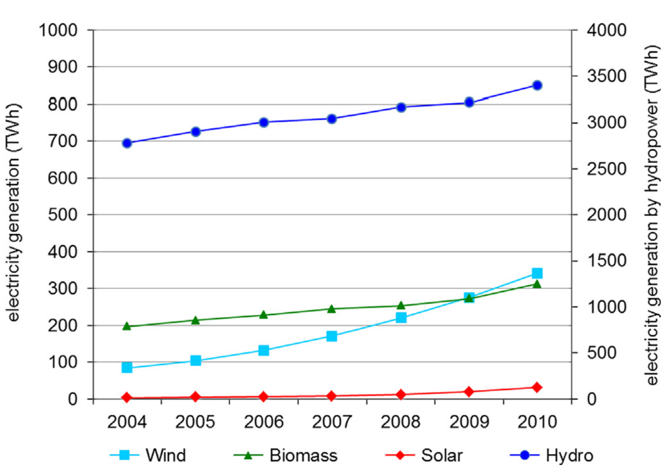


Fig. 1. Electricity generation of renewables worldwide (data from US Energy Information Administration – International Energy Statistics). Please note the scaling of the second *y*-axis representing electricity generation by hydropower.

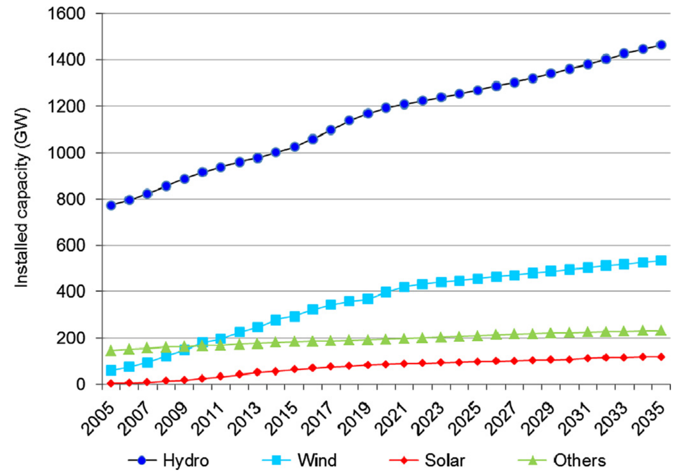


Fig. 2. Installed capacity of renewables worldwide with outlooks under a reference scenario until 2035 (data from US Energy Information Administration – International Energy Outlook 2011 [18]). (*"Non-marketed (noncommercial) biomass from plant and animal resources, while an important source of energy, particularly in the developing non-OECD economies, is not included in the projections, because comprehensive data on its use are not available. For the same reason, off-grid distributed renewable – renewable energy consumed at the site of production, such as off-grid photovoltaic (PV) panels – are not included in the projections"* [21]).

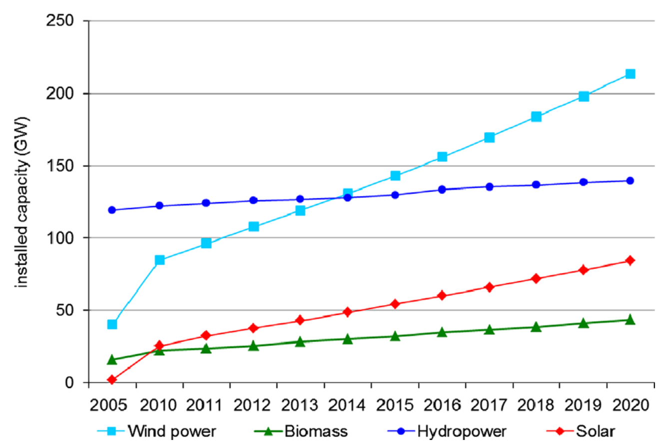


Fig. 3. Future projections of installed capacity of renewables in the EU from 2010 to 2020 compared to data from 2005. Data from [4].

energy sources decreased in the EU-member states from ca. 94% (288.8 TWh) in 1990 to ca. 58% (327.4 TWh) in 2008 [20]. However, in the EU member states much more electricity (291 TWh) was generated in 2009 by 1681 large hydropower plants with an installed capacity of >10 MW compared to 45.9 TWh generated by 20,585 small hydropower plants (installed capacity of <10 MW) [23].

Future projections of installed capacity in the EU for the four main renewables by the Energy Research Centre of the Netherlands (ECN) based on the National Renewable Energy Action Plans (NREAP) depict a different trend for hydropower compared to wind, solar and biomass (Fig. 3). The data were provided by the 27 EU member states according to Article 4 of the European Renewable Energy Directive (2009/28/EC). The strongest increase (from ca. 25 GW in 2010 to 84 GW in 2020) is projected for solar power and wind (85 GW in 2010 to 213 GW in 2020), hydropower (excl. pump storage facilities) is expected to increase very slightly from 122 GW in 2010 to 144 GW in 2020 [24].

With increasing electricity supply by wind and solar energy that cannot be delivered constantly or adequately to meet the particular electricity demand throughout the year, more electrical storage possibilities will be needed to compensate for fluctuating

grid frequency. Pumped-storage hydro plants are actually the most economic possibility to store surplus electricity generation. Furthermore storage of water volumes can be used to capture high prices during times of peak demand [20]. Actually approximately 50 large pumped-storage hydro plants with an installed capacity of >1 GW installed capacity are in operation. Most of them are located in Asia (25 plants with an total installed capacity of ca. 32 GW) followed by Europe with 12 plants (ca. 15 GW installed capacity in total) and North America (10 plants with ca. 15 GW). In Africa and Australia one large pumped-storage hydro plant is in operation [25]. Several projects to build new or to expand existing pump storage plants will be realized during the next years in Europe, offering the facility to connect electricity grids in Europe for optimized use and storage of electricity generated by renewables [26]. One of the first steps towards this development is the network connection between Norway and Germany (but also between other countries around the North Sea) to use large hydropower schemes to store electricity that will be generated from off-shore wind parks [27].

2.1. Hydropower in Germany

Installed capacity of electricity generation by renewables significantly increased during the last years in Germany, with remarkable increment especially for solar energy, but also for wind and biomass, while hydropower capacity remained almost constant (Fig. 4).

The shares of renewables to total electricity generation in Germany were 20.0% (121,939 GWh) in 2011, with the highest contribution of wind, biomass (including biogenic share of waste) and hydro (Fig. 4). The estimated long-term potential for electricity generation by renewables in Germany is expected to be the highest for wind (on- and off-shore), solar, geothermal and biomass. The potential of hydropower seems to be almost exploited (Fig. 5).

The estimated potential of total electricity generation by renewables would surpass the electricity consumption of Germany in 2009 (617,000 TWh) by 20% [22].

However, Germany is leading in the number of small hydropower plants among the member states of the EU with 7512 SHP, but due to the vast majority of SHP (7195) with an installed capacity of <1 MW the total gross electricity generation of SHP is only 8043 GWh. Mean electricity generation of 1.1 GWh per SHP is therefore rather low in relation to the high number of SHP (Fig. 6). Number of SHP in other EU member states were significantly lower than in Germany (Austria comes second with 2433 SHP) but the mean electricity generation per

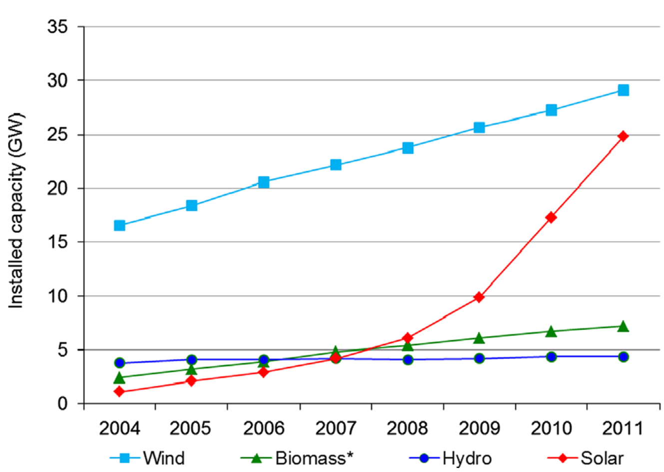


Fig. 4. Installed capacity of renewables in Germany from 2004 to 2011 (*biomass includes amounts of biogenic share of waste). Data from [8].

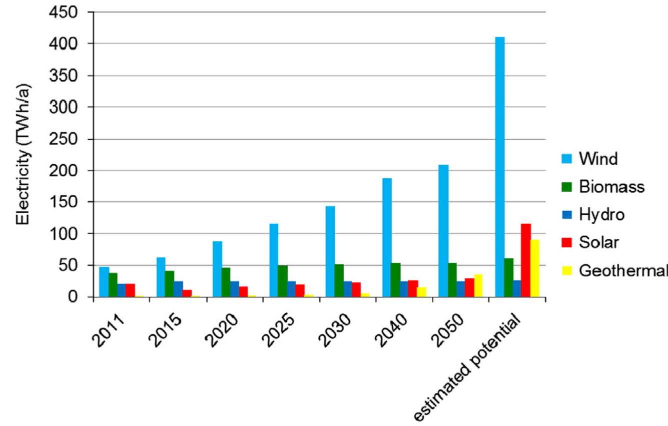


Fig. 5. Electricity generation from renewables in Germany in 2011, future prospects and estimated long-term potentials. Wind includes on- and off-shore, biomass includes amounts of biogenic share of waste. Data for 2011 from [28], estimated potentials of electricity generation according to [22], future prospects according to [8].

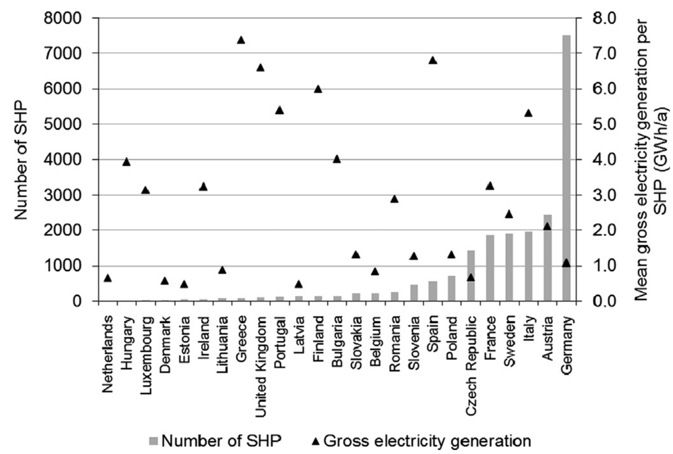


Fig. 6. Number of small hydropower projects (SHP) and mean gross electricity generation of SHP by country for 25 EU-member states (without Cyprus and Malta) in 2009. Data from the database "Streammap" of the European Small Hydropower Association [23].

SHP was mainly higher in most countries especially for Greece (7.4 GWh), Spain (6.8 GWh) and United Kingdom (6.6 GWh). Shares of large hydropower (installed capacity >10 MW) contributing ca. 58% and medium sized hydropower (1–10 MW) contributing ca. 25% to gross electricity generation by hydropower in Germany were significantly higher during the last years than small hydropower (<1 MW) with a share of 17% [23]. The technical potential for hydropower use in Germany was estimated to range between 33.2 and 42.1 TWh according to a recent study commissioned by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety [29].

A special report from the German Advisory Council on the Environment [27] described different scenarios in which a transition of the today energy mix to a wholly renewable electricity supply by 2050 is believed to be feasible. This special report assumed that the hydro power potential for electricity generation in Germany is limited to about 28 TWh/a for orographic reasons. Thus, the additional development potential of hydropower is rated to be minimal. In 2011 only one run-of-river hydropower project (refurbishment to increase the installed capacity of an existing plant for 38 MW) but five pumped-storage hydro plants (four new plants with an installed capacity of 2.045 MW and one refurbishment to increase the installed capacity of an existing plant for 200 MW) were listed among 66 power plant projects in Germany [30].

In general main aspect of increasing electricity generation by hydropower in Germany is the refurbishment (measures which increase installed capacity in existing hydropower plants) and modernization and maintenance of existing plants (measures which increase electricity production and in the same time contribute to ecological improvement, e.g. new turbines according to the best available techniques/good environmental practice) [31].

2.2. Electricity and hydropower in Saxony

Saxony is a federal state of Germany with an area of approximately 18,500 km² and a total population of 4.3 million inhabitants. It shares the two large river basin districts of the Elbe and Odra with the neighbor states of Poland and the Czech Republic. Installed capacity to generate electricity in Saxony was mainly by power plants using fossil fuels (4598 MW) with the highest share of coal-fired power plants, mainly lignite (3.866 MW) while renewables including storage pump hydropower (1272 MW) provided an installed capacity of 2552 MW, to which run-of-river hydropower contributed 3.2% [32].

Electricity generation by hydropower (without pump storage) increased in Saxony from 1991 (43 GWh/a) to 325 GWh/a in 2010. Thus, hydropower ranged in third place compared to other renewable energy sources, with the highest electricity generation by wind power (1336 GWh/a) followed by biomass (1235 GWh/a). Sine 2002 electricity generation by other renewable energy sources significantly increased in Saxony, while hydropower remained relatively constant (Fig. 7).

Use of hydropower has a long history in Saxony already beginning in the medieval using wooden water mills and for dewatering of mines in the Ore Mountains. The first run-of-river hydropower plant in Saxony generated in 1882 electricity from the medium sized stream Flöha in the town Olbernhau [33]. Today numerous streams were used for electricity generation by small hydropower plants with an installed capacity <1 MW while only nine hydropower plants with an installed capacity >1 MW exist in Saxony. Additionally, two pump storage plants, intrinsically net consumer of energy due to the loss of energy (15–30%) that can be regained from the energy used to pump water from a river reservoir into an elevated reservoir [13], located in Markersbach (installed capacity of 1050 MW) and, one of the oldest pump storage plants worldwide, in Niederwartha near Dresden (120 MW) are used to generate electricity from hydropower. The highest installed capacity of hydropower plants in Saxony are 7.9 MW of the dam Kriebstein and 1.7 MW of the dam Eibenstock (a drinking water reservoir).

In 2009 ca. 300 small hydropower plants with an installed capacity of totally 88 MW generated electricity in Saxony. Main

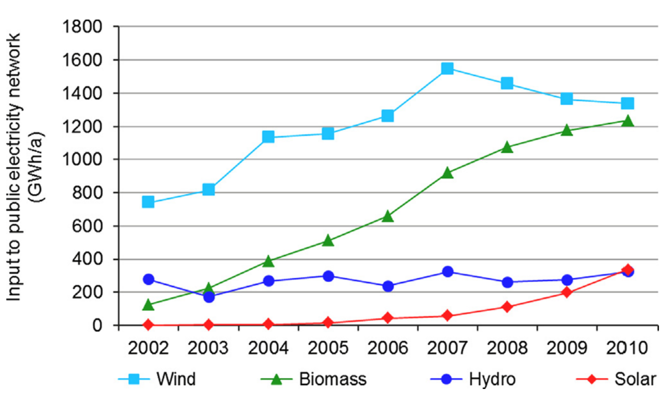


Fig. 7. Input of electricity into the public electricity network of the five most important renewable energy sources in Saxony from 2002 to 2010 (data from the Saxony State Office for Statistics).

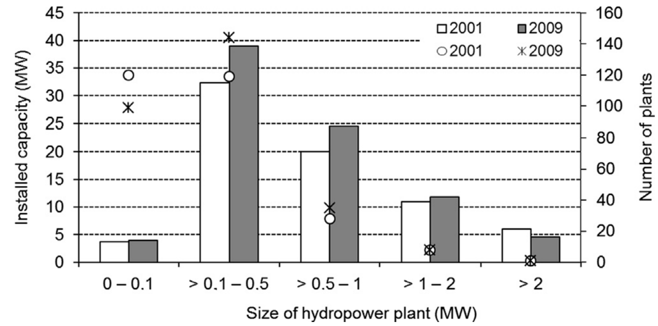


Fig. 8. Installed capacity and number of hydropower plants in Saxony connected to the public electricity network in 2001 and 2009, separated by size of the hydropower plants (data from the Sächsische Energieagentur GmbH).

shares (46.5%) of electricity were generated by small hydropower schemes with an installed capacity between 0.1 and 0.5 MW (Fig. 8).

Data from the 50Hertz Transmission GmbH (www.50hertz.com) responsible for the operation, maintenance, planning, and expansion of the 380/220 kV transmission grid throughout the northern and eastern part of Germany displayed in the annual bill for 2011 a total electricity generation of ca. 261 GWh from 295 hydropower plants in Saxony. For this energy supply a remuneration of ca. 27 Mio. € was paid according to the feed-in-tariffs of the Renewable Energies Act. Furthermore, in 2012 the number of hydropower plants enjoying renewable energy subsidies increased to 311 schemes with a total installed capacity of ca. 90 GW. Most recently available data displayed 366 hydropower plants with an installed capacity of ca. 91 GW in Saxony (Fig. 9). Some of these plants are not in use and therefore do not generate electricity. Most of the plants are located in the upland region of Saxony (>200 m above sea level) and along the larger streams (Zschopau and its larger tributaries) and rivers (Zwickauer and Freiberger Mulde and some tributaries). In the eastern part of Saxony hydropower plants are located mainly along the rivers Spree and Lausitzer Neiße.

The most widely used turbine technology in Saxony is the Francis turbine contributing to 47% of all hydropower plants. Second most turbine technology is the Kaplan turbine (29%) followed by water wheels (16.5%). Cross-flow (Ossberger) turbines are more seldom in use (6%), whereas only two Pelton turbines are actually in operation. Furthermore three hydropower plants in Saxony use new technologies: one DIVE (a novel generator type that can handle very high torques at low speeds with the possibility to realize a direct connection of the turbine runner and the generator runner (without gearbox or belt drive), one water vortex (water flows into a round basin and down towards a central drain building a vortex. This technology is intended to work at low heads and can be developed to use generators of any size up to 1 MW, depending on flow, head, and basin diameter) and one screw turbine.

2.3. Hydropower and the environmental objectives of the WFD

Principally, the use of small hydropower and the environmental objectives of the WFD must not necessarily collide, but the main difficulty is often to find an acceptable compromise between the commercial interest of the operator and the environmental demands on construction and operation of small hydropower plants. The results of a workshop on Water Framework Directive & Hydropower held in Berlin, 2007 summarized problems but also some solutions to bring the two different topics more closely together [34]. Main problem of hydropower is the alteration of the natural hydrology and sediment transport, the disruption of

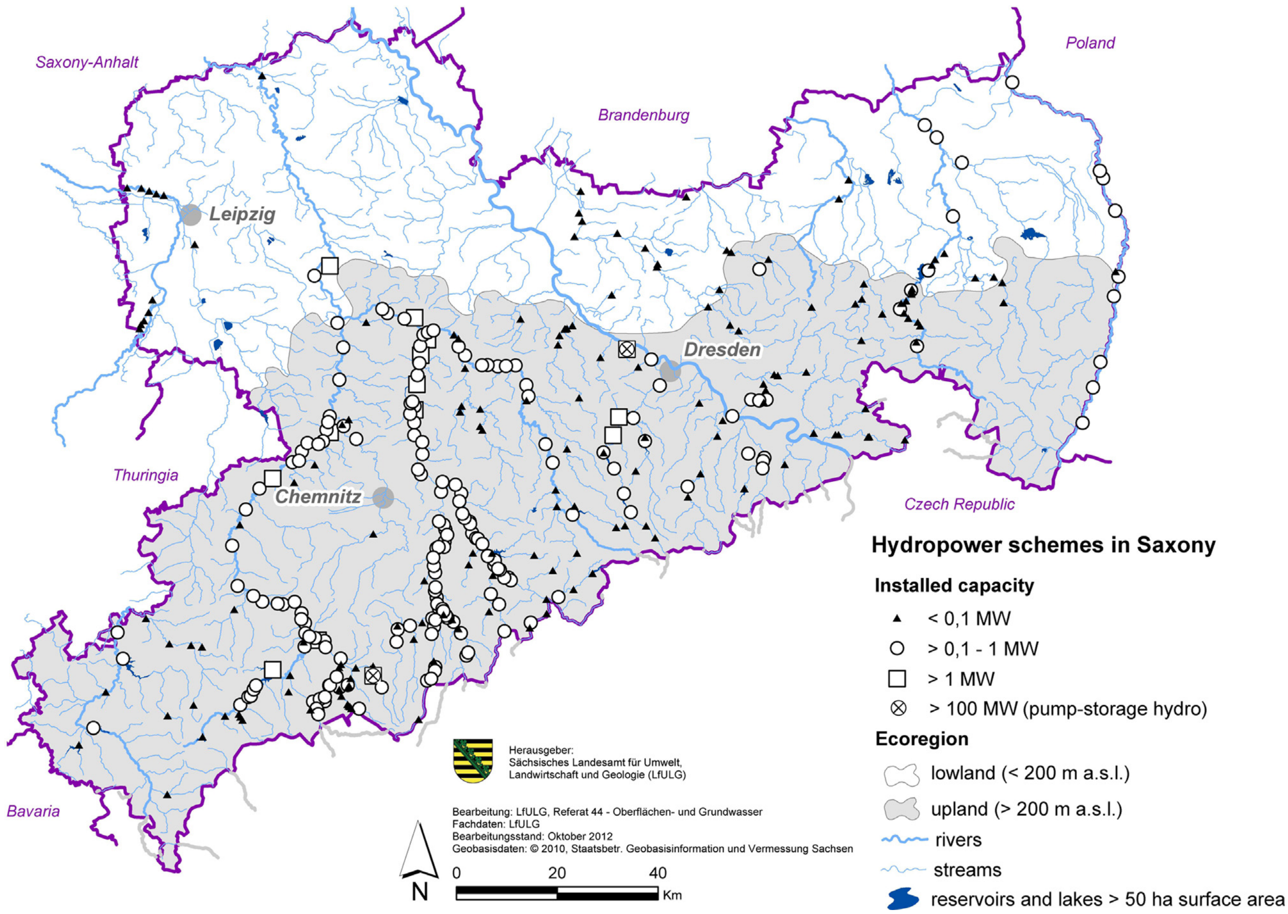


Fig. 9. Location of hydropower plants in Saxony classified by the installed capacity.

biological continuity and in the case of diversion schemes the need for an ecological residual flow that must remain in the natural stream course and therefore cannot be used for electricity generation [35]. Furthermore, hydropower schemes can cause lethal or sublethal damage to downstream migratory fishes that pass the turbines. The negative effects of small hydropower plants on eels (*Anguilla anguilla*) [36,37] and salmonids (*Salmo trutta* and *Salmo salar*) [38,39] are well known. Modern technologies might be helpful to reduce these negative effects by appropriate mitigation measures [12]. However, these mitigation measures like intake trashracks that prevent fish (especially small stages) from entering the turbines, fish ladders to provide migration pathways for fishes or ecological minimum residual flows for hydropower plants with diversion channels could affect the economy of the particular station. Furthermore the effectiveness of the measures to mitigate the negative influences can be very different. Residual flows must be released by the operator of a hydropower plant who is also responsible for the maintenance of fish ladders (e.g. warranty of function as a pathway for fishes). If these legal requirements were not fulfilled, then the measures will be not effective [35].

Studies on the effects of small hydropower on benthic invertebrates showed an indifferent picture as most investigated streams were already affected by multiple stressors such as human land use in the particular watershed that could confound detection of hydropower specific responses [40]. However, alterations of the natural stream flow by diversion dams can cause significant changes in benthic invertebrate communities [41] and sediment as well hydraulic conditions [42] that can negatively affect ecosystem functioning. Some studies showed that an increasing number of small low head dams and weirs not only for hydropower purposes but altering the natural flow and the biological continuity of a stream can significantly affect invertebrate and fish communities [43]. Although the environmental problems caused by small hydropower were often believed to be rather marginal due to the local aspect of few hundred meters of tailback and diversion stretches [13,15] the negative effects must be viewed in the context of the ecological status of the whole stream considering all anthropogenic pressures that affect the particular stream ecosystem. Furthermore, the cumulative environmental effect of small hydropower has to be considered if many more new dams for hydropower utilization were considered to be constructed [44].

Actually, only 8% of all streams in Germany [45] and 4% of streams and rivers in Saxony achieved the ecological objective demanded by the EU Water Framework Directive (WFD). Most of the streams and rivers are subjected to flow regulations and morphological alterations. Additionally, several streams and rivers are also affected by nutrient rich influent from urban settlements including waste water treatment plants and surface runoff from arable fields. On-site river habitat surveys were conducted for all streams and rivers that are part of the reduced stream system used for reporting to the European Commission for implementation of the WFD [46]. The river habitat survey rates the extent of morphological degradation compared to natural reference conditions into seven classes from 1 (no deviation from reference conditions) to 7 (completely modified) and revealed that only 11% of stream and river lengths in Saxony were rated as moderately or less modified. For these stream sections it is assumed that habitat quality will be appropriate for the establishment of a stream specific fauna and flora, while at least 82% of the Saxony stream reaches will need improvement of habitat quality (remaining 7% could not be rated due to lack of data). Alterations of stream morphology were mainly caused by technical construction

(straightening as well as stream bed and bank reinforcement) within urban settlements and straightening and deepening in catchments with intensive agricultural land use. Furthermore, approximately up to 8000 weirs and dams of different heights (from 20 cm to several meters) and built for different purposes impair the biological continuity of the streams and water abstractions e.g. by hydropower diversion schemes can aggravate the negative effect of other pressures. Especially loads of nutrient rich sediments from arable fields washed into the streams by surface runoff can lead to an increased deposition of fine sediments in stream reaches below diversion dams [42].

2.4. Prospects of hydropower in Saxony

Objectives of the climate and energy policy of Saxony will be the increase of renewable shares to total gross electricity generation from 12.5% (2628 GWh/a) in 2007 to 24.3% (5130 GWh/a) in 2020 (assuming a constant gross electricity consumption of 21.100 GWh/a in Saxony). Contribution of hydropower to this increase of renewable shares is expected to be rather low (increase of share from ca. 1.4% in 2007 to ca. 1.5% in 2020 of the total gross electricity consumption). Thus, hydropower will have the lowest development potential compared to wind, biomass and solar energy in Saxony (Fig. 10).

The economic potential of hydropower in Saxony is estimated to be around 320 GWh/a [44], although other studies considered a potential of 433 GWh/a to be feasible [48]. The latter study described an additional potential of totally 456 new hydropower facilities at existing weirs and dams with a total installed capacity of 36 MW. These 456 hydropower schemes were separated into 92 with an installed capacity of >0.1 MW, 114 schemes with >0.04 MW and 250 schemes with an installed capacity <0.04 MW. Thus, in Saxony at the best the construction of only few small and some minihydropower plants seems to be possible. However, with respects to the environmental demand to improve the ecological status of the majority of streams and rivers in Saxony the potential to render new run-of-river hydropower sources seems to be almost exhausted. The recent study of the hydropower potential in Germany commissioned by the German Federal Ministry for Environment, Nature Conservation and Nuclear Safety [29] demonstrated the limited potential especially for the construction of completely new hydropower plants, but shows the potential to increase the electricity generation capacity by improvement of plant operation (technical efficiency), refurbishment or modernization (exchange of old-fashioned components by new technologies).

Actually, existing weirs and dams in Saxony are superficially under review according to German water law whether a removal of the particular construction is necessary for achievement of the good ecological status or potential of the stream according to the environmental objectives of the WFD. All dams and weirs for which the removal is rated to be not necessary should be proved for an economic hydropower use by local conditions such as effective head and discharge, considering other possible site specific demands of nature conservation, recreation or else.

The potential use of decentralized mini- and microhydropower techniques has been recently summarized for Saxony [49], considering innovative developments like archemedean screws or water vortex power plants.

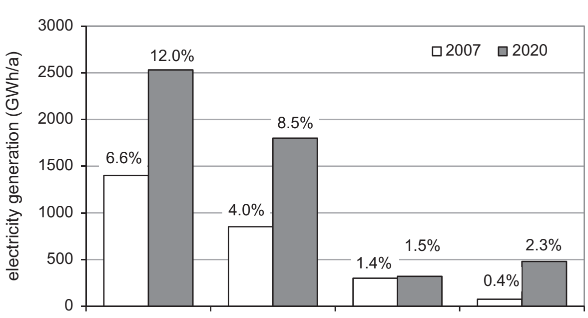


Fig. 10. Shares of renewables to electricity generation in Saxony comparing data from 2007 to prospects for 2020 [47].

3. Conclusions

Further developmental potential of hydropower in Germany and Saxony is generally low and could be mainly achieved by refurbishment or modernization of existing facilities and improvement of plant operation. Construction of completely new facilities at existing dams could be exceptional feasible but almost all the best available sites for hydropower are already exploited in Germany. Possible losses of electricity generation by hydropower caused by ecological demands such as increased ecological residual flows in diversion stretches, fish ladders or intake trash racks could be compensated by modern and innovative technologies. Economic losses for hydropower operators could be also compensated by higher feed-in tariffs for electricity from renewable sources as already usual in Germany and many other European countries.

Future potentials of hydropower in Europe seem to be very different as the status of industrial development and main goals of energy policy are very different between European regions. Countries with mountainous regions, especially in the Alpine region, and some eastern countries, especially Turkey, with increasing electricity demand for industrial purposes will surely expand the use of hydropower to generate or store electricity. The developmental potential of hydropower in those countries without remaining favorable sites to exploit and an almost completed development of industrial growth and electricity generation will be surely much lower. The challenge for Europe will be the establishment of an international electricity network that will optimize the generation, transport and storage of renewable electricity from producers to users with respect to highly fluctuating demands.

Hydropower will remain the outstanding renewable source for electricity generation worldwide during the next decades. However, increase of installed capacity will be mainly gained by new large hydropower schemes especially in Asia but also in South America and the Russian Federation. Nevertheless, the expansion of small and mini hydropower use seem to be more likely in countries with increasing demand of rural electrification. For these countries small hydropower could be economic and ecologic solutions for electricity generation if modern technologies for construction and operation will be applied in consideration of site specific ecological aspects.

References

[1] IPCC. Summary for policymakers. In: Edenhofer O, Pichs-Madruga R, Sokona Y, Seyboth K, Matschoss P, Kadner S, Zwickel T, Eickemeier P, Hansen G, Schlomer S, von Stechow C, editors. IPCC special report on renewable energy sources and climate change mitigation. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press; 2011.
[2] International Energy Agency. Key world energy statistics. Paris: IEA; 2011. 〈http://www.iea.org/statistics/〉.
[3] International Energy Agency. World energy outlook. Paris: IEA; 2010; 2010.
[4] Renewables. Global Status Report. Renewable energy policy network for the 21st century. Paris: REN21; 2013.
[5] Huang H, Yan Z. Present situation and future prospect of hydropower in China. Renewable Sustainable Energy Rev. 2009;13:1652–6.
[6] World Energy Council. Survey of energy resources interim update 2009. London, United Kingdom. 〈http://www.worldenergy.org/documents/ser_interim_update_2009_final.pdf〉 (accessed 07.03.13).

[7] International Energy Agency. Energy policies of IEA countries – Germany. Paris: IEA; 2007.

[8] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Weiterentwicklung der Ausbaustrategie Erneuerbare Energien – Leitstudie 2008. Bonn; 2008. 〈http://www.erneuerbare-energien.de〉.

[9] European Commission. Hydropower generation in the context of the EU WFD. Study commissioned by the European Commission, DG Environment – Unit SRD.3. 2011, Brussels; 2010. 〈http://circabc.europa.eu/sd/d/30689efe-0f16-4ee5-a271-f46fcb0789f0/11418_WFD_HP_final%20110516.pdf〉 (accessed 07.03.13).

[10] European Commission. Directive 2000/60/EC of the European parliament and of the council establishing a framework for community action in the field of water policy. Brussels, Luxembourg; 2000.

[11] European Small Hydropower Association. Current status of small hydropower development in the EU-27. 〈http://www.streammap.esha.be/fileadmin/documents/Raising_awareness_doc___press_release/FINAL_SHP_Awareness_2011.pdf〉 (accessed 07.03.13).

[12] European Small Hydropower Association. Environmental integration of small hydropower. 〈http://www.esha.be/fileadmin/esha_files/documents/publications/publications/Brochure_EN.pdf〉 (accessed 07.03.13).

[13] Lenzen M. Current state of development of electricity-generating technologies: a literature review. Energies 2010;3:462–591, http://dx.doi.org/10.3390/en3030462.

[14] Renewables, Global Status Report. Renewable energy policy network for the 21st century. Paris: REN21; 2011.

[15] Paish O. Small hydro power: technology and current status. Renewable Sustainable Energy Rev. 2002;6:537–56.

[16] International Renewable Energy Agency. Renewable energy technologies: cost analysis series. Hydropower. Abu Dhabi, United Arab Emirates; 2012.

[17] Ogayar B, Viodal PG, Hernandez JC. Analysis of the cost for the refurbishment of small hydropower plants. Renewable Sustainable Energy Rev. 2009;34: 2501–9.

[18] Bhutto AW, Bazmi AA, Zahedib G. Greener energy: issues and challenges for Pakistan-hydel power prospective. Renewable Sustainable Energy Rev. 2012;16: 2732–46.

[19] Renewables. Global Status Report. Renewable energy policy network for the 21st century. Paris: REN21; 2010.

[20] Renewables. Global Status Report. Renewable energy policy network for the 21st century. Paris: REN21; 2012.

[21] US Energy Information Administration. International Energy Outlook. Washington, DC, USA; 2011. 〈http://www.eia.gov/forecasts/ieo/pdf/0484(2011).pdf〉 (accessed 07.03.13).

[22] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Erneuerbare Energien in Zahlen – Nationale und internationale Zahlen. Bonn; 2010. 〈http://www.bmu.de/erneuerbare_energien/downloads/doc/2720.php〉.

[23] European Small Hydropower Association. Database "STREAMMAP". Brussels, Belgium. 〈http://www.streammap.esha.be/14.0.html〉.

[24] Energy Research Centre of the Netherlands. Renewable energy projections as published in the national renewable energy action plans of the European member states. Petten, Netherlands; 28 November 2011. 〈http://www.ecn.nl/units/ps/themes/renewable-energy/projects/nreap/〉 (accessed 07.03.13).

[25] List of pumped-storage hydroelectric power stations. 〈http://en.wikipedia.org/wiki/List_of_pumped-storage_hydroelectric_power_stations〉 (accessd 19.09.13).

[26] Zuber M. Renaissance for pumped storage in Europe. Extract from the report The European Market for Pumped-Storage Power Plants 2011/2012 published online. 〈http://www.renewableenergyworld.com/rea/news/article/2011/08/renaissance-for-pumped-storage-in-europe〉.

[27] German Advisory Council on the Environment. Pathways towards a 100% renewable electricity system. Geschäftsstelle des Sachverständigenrates für Umweltfragen (SRU). Berlin, Germany. 〈http://www.umweltrat.de/SharedDocs/Downloads/EN/02_Special_Reports/2011_10_Special_Report_Pathways_renewables.pdf?__blob=publicationFile〉.

[28] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Development of renewable energy sources in Germany 2011. Bonn; 2012. 〈http://www.erneuerbare-energien.de/files/english/pdf/application/pdf/ee_in_deutschland_graf_tab_en.pdf〉.

[29] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Potentialermittlung für den Ausbau der Wasserkraftnutzung in Deutschland als Grundlage für die Entwicklung einer geeigneten Ausbaustrategie. Bonn; 2011.

[30] Weltenergierat – Deutschland e.V. Energie für Deutschland 2011. Berlin; 2011. 〈http://www.worldenergy.org/documents/energie_fr_deutschland_2011l.pdf〉 (accessed 07.03.13).

[31] Common Implementation Strategy Workshop. Water management, Water Framework Directive & Hydropower. Common Implementation Strategy Workshop, Brussels; November 2011. Issue Paper 〈https://circabc.europa.eu/sd/d/23d94d2d-6b9c-4f17-9e15-14045cd541f3/Issue%20Paper_final.pdf〉 (accessed 07/03/2013).

[32] Energie- und Klimaprogramm Sachsen. (Entwurf, Stand 12. Oktober 2011).

[33] Rindelhardt U. Wasserkraftnutzung in Ostdeutschland. Wasserwirtschaft 2007;97(6):33–6.

[34] Common Implementation Strategy Workshop. Water Framework Directive & Hydropower. Workshop summary report. Berlin; 2007. 〈http://www.ecologic-events.de/hydropower/documents/summary_report.pdf〉 (accessed 07.03.13).

[35] Baskaya S, Baskaya E, Sari A. The principal negative environmental impacts of small hydropower plants in Turkey. Afr. J. Agric. Res. 2011;6:3284–90, http://dx.doi.org/10.5897/AJAR10.786.

[36] Calles O, Olsson IC, Comoglio C, Kemp PS, Blunden L, Schmitz M, Greenberg LA. Size-dependent mortality of migratory silver eels at a hydropower plant, and implications for escapement to the sea. Freshwater Biology, vol. 55, 2010, pp. 2167–2180. doi:10.1111/j.1365-2427.2010.02459.x.

[37] Travade F, Larinier M, Subra S, Gomes P, De-Oliveira E. Behaviour and passage of European silver eels (*Anguilla anguilla*) at a small hydropower plantduring their downstream migration. Knowl. Manage. Aquat. Ecosystems 2010;398:1–17, http://dx.doi.org/10.1051/kmae/2010022.

[38] Almodovar A, Nicola GG. Effects of a small hydropower station upon brown trout *Salmo trutta* L. in the River Hoz Seca (Tagus basin, Spain) one year after regulation. Regul. Rivers: Res. Manage. 1999;15:477–84.

[39] Thorstad EB, Whoriskey F, Uglem I, Moore A, Rikardsen AH, Finstad B. A critical life stage of the Atlantic salmon *Salmo salar*: behaviour and survival during the smolt and initial post-smolt migration. J. Fish Biol. 2012;81:500–42, http://dx.doi.org/10.1111/j.1095-8649.2012.03370.x.

[40] Andrew Rehn C, Natalia von Ellenrieder, Ode Peter R. Assessment of ecological impacts of hydropower projects on benthic macroinvertebrate assemblages: a review of existing data collected for FERC relicensing studies. California Energy Commission, PIER Energy-Related Environmental Research Program. 2008. CEC-500-2007-040.

[41] Walters AW, Post DM. How low can you go? Impacts of a low-flow disturbance on aquatic insect communities Ecol. Appl. 2011;21:163–74.

[42] Baker DW, Bledsoe BP, Albano CM, Poff NL. Downstream effects of diversion dams on sediment and hydraulic conditions of Rocky Mountain streams. River Res. Appl. 2010;27:388–401, http://dx.doi.org/10.1002/rra.1376.

[43] Santucci VJ, Gephard SR, Pescitelli SM. Effects of multiple low-head dams on fish, macroinvertebrates, habitat and water quality in the Fox River, Illinois. North Am. J. Fish. Manage. 2005;25:975–92.

[44] Abbasi T, Abbasi SA. Small hydro and the environmental implications of its extensive utilization. Renewable Sustainable Energy Rev. 2011;15:2134–43.

[45] Bundesministerium für Umwelt, Naturschutz und Reaktorsicherheit (BMU). Die Wasserrahmenrichtlinie – Ergebnisse der Bewirtschaftungsplanung 2009 in Deutschland. Bonn; 2010 〈http://www.bmu.de/files/pdfs/allgemein/application/pdf/broschuere_wasserrahmenrichtlinie_bf.pdf〉.

[46] Spänhoff B, Dimmer R, Friese H, Harnapp S, Herbst F, Jenemann K, Mickel A, Rohde S, Schönherr M, Ziegler K, Kuhn K, Müller U. Ecological status of rivers and streams according to water framework directive in Saxony (Germany) and prospects of improvement. Water 2012;4:887–904, http://dx.doi.org/10.3390/w4040887.

[47] Sächsisches Staatsministerium für Umwelt und Landwirtschaft (SMUL). Hintergrundpapier zu den Zielen der künftigen Klimaschutz und Energiepolitik des Freistaates Sachsen. Dresden; 2009. 〈http://www.umwelt.sachsen.de/umwelt/klima/18591.htm〉.

[48] Kreibich E. Wasserkraftnutzung. In: Grüne Ausbaustudie 2020 – Perspektiven für Erneuerbare Energien in Sachsen; 2008. 〈http://www.gruene-fraktion-sachsen.de/publikationen.html〉.

[49] Sächsisches Staatsministerium für Umwelt und Landwirtschaft (SMUL). Dezentrale Nutzung erneuerbarer Energien im ländlichen Raum Sachsens. Dresden; 2012. 〈http://publikationen.sachsen.de/bdb/artikel/10872〉 (accessed 07.03.13).